Normal and Abnormal Prosthetic Valve Function as Assessed by Doppler Echocardiography

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Doppler echocardiography was performed in 136 patients with a normally functioning prosthetic valve in the aortic (n = 59), mitral (n = 74) and tricuspid (n = 3) positions. These included patients with St. Jude (n = 82), Björk-Shiley (n = 18), Beall (n = 13), Starr-Edwards (n = 7) or tissue (n = 16) valves. Peak and mean pressure gradients across the prostheses were measured using the simplified Bernoulli equation. The prosthetic valve orifice (PVO, in square centimeters), only in the mitral position, was calculated by the equation: PVO = 220/pressure half-time.

In the aortic position, the St. Jude valve had a lower peak velocity (2.3 ± 0.6 m/s, range 1.0 to 3.9), peak gradient (22 ± 12 mm Hg, range 4 to 61) and mean gradient (12 ± 7 mm Hg, range 2 to 32) than the other valves ($p < 0.05$ when compared with Starr-Edwards). In the mitral position, the St. Jude valve had the largest orifice (3.0 ± 0.6 cm^2, range 1.8 to 5.0) ($p < 0.0001$ compared with all other valves). Insignificant regurgitation was commonly found by pulsed mode Doppler technique in patients with a St. Jude or Björk-Shiley valve in the aortic or mitral position and in patients with a Starr-Edwards or tissue valve in the aortic position. In 17 other patients with a malfunctioning prosthesis (four St. Jude, two Björk-Shiley, four Beall and seven tissue valves) proven by cardiac catheterization, surgery or autopsy, Doppler echocardiography correctly identified the complication (significant regurgitation or obstruction) in all but 2 patients who had a Beall valve.

It is concluded that 1) the St. Jude valve appears to have the most optimal hemodynamics; mild regurgitation can be detected by the Doppler technique in normally functioning St. Jude and Björk-Shiley valves in the aortic or mitral position and in Starr-Edwards and tissue valves in the aortic position, and 2) Doppler echocardiography is a useful method for the detection of prosthetic valve malfunction, especially when the St. Jude, Björk-Shiley and tissue valves are assessed.

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Several noninvasive techniques including phonocardiography, M-mode and two-dimensional echocardiography and cinefluoroscopy have been used to assess prosthetic valve function (1). All these techniques have limitations in detecting complications related to the prosthetic valves, and their usefulness may differ in the various types of prostheses (1,2). Doppler echocardiography is a reliable method for quantifying the pressure gradient across native stenotic aortic or mitral valves (3) and in detecting even mild degrees of aortic or mitral regurgitation (4,5). The Doppler flow characteristics of normally functioning individual prosthetic valves have been reported (6–8), whereas only rare reports exist describing the use of Doppler echocardiography in detecting prosthetic valve malfunction (9–11).

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In this study, we compare the Doppler flow characteristics and pressure gradients of various normally functioning mechanical and tissue prosthetic valves in 136 patients. In addition, the Doppler echocardiographic findings of 17 patients with complications related to the prosthesis are described.

Methods

Study patients. During 1 year, 136 consecutive patients with a normal prosthetic valve were referred for a routine baseline or follow-up postoperative echocardiographic study. These patients were asymptomatic and had a normal physical examination. Their age ranged from 15 to 83 years (mean 60 ± 14); there were 76 men and 60 women. The prosthesis was in the aortic position in 59 patients, in the mitral position in 74 and in the tricuspid position in 3. A metallic prosthetic valve was present in 120 patients (82 had a St. Jude bileaflet valve, 18 had a Björk-Shiley tilting disc valve, 13 had a Beall valve and 7 had a Starr-Edwards ball valve). A tissue prosthetic valve was present in 16

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patients; 5 had a Carpentier-Edwards, 5 had a Hancock and 6 had an Ionescu-Shiley valve. In addition, the study included 17 other patients (4 with a St. Jude, 2 with a Björk-Shiley, 4 with a Beall and 7 with a tissue prosthesis) who were studied by Doppler echocardiography and subsequently were proven to have complications related to the prosthetic valve by cardiac catheterization, surgery or autopsy.

Doppler echocardiography. Doppler echocardiographic studies were performed with the Irex-Exemplar or Irex-Meridian phased array system; both these systems are equipped with pulsed and continuous mode Doppler ultrasound. The Doppler examination was performed by the same technician utilizing a 2 MHz independent Pedoff transducer or a simultaneous two-dimensional and Doppler imaging transducer. The sample size of the pulsed mode Doppler technique is 7 × 7 mm and at a depth of 7 to 8 cm a peak velocity of 2.0 to 2.2 m/s can be measured. Velocities up to 6 m/s can be measured with the continuous mode Doppler technique. The Doppler output signal was displayed in a spectral format on a strip chart recorder with a paper speed of 50 mm/s and provided both the direction of the blood flow and its peak flow velocity.

The velocity profiles across the prosthetic valve were obtained by placing the transducer in the apical position in patients with a mitral or tricuspid prosthesis and in the apical, suprasternal or right parasternal position in patients with an aortic prosthesis (Fig. 1 and 2). The Doppler transmit beam was placed as perpendicular as possible to the plane of the valve ring in patients with a central flow valve; some angulation was required to obtain the maximal flow velocity in patients with an eccentric flow valve. The initial positioning of the sample volume of the pulsed Doppler technique was made with the aid of two dimensional imaging. The audio output guided final positioning until an optimal spectral signal was obtained. After data were obtained in the pulsed mode, the equipment was switched to continuous mode to confirm that the maximal velocities had been recorded. To interrogate for the presence of prosthetic valve regurgitation, the left atrium was examined in patients with a prosthetic mitral valve and the left ventricular outflow tract was examined in patients with an aortic valve prosthesis using parasternal and apical windows.

Measurements. Peak transvalvular velocity was measured in meters per second and was taken as the maximal recorded velocity that showed a continuous envelope and a well defined peak. Using the modified Bernoulli equation, $P = 4 \times V2$, where P = pressure gradient and V = maximal velocity in meters per second, the peak pressure gradient (in millimeters of mercury) was calculated. The mean transvalvular gradient was estimated either by dividing the velocity profile every 0.04 second and averaging the measurements or by a recently introduced Irex analysis and calculation package. In patients with a mitral valve prosthesis, the pressure half-time in milliseconds ($P\frac{1}{2}$) was measured and the mitral valve orifice (in square centimeters) was calculated by the equation: $220/P\frac{1}{2}$ (3). All calculations were the average of three cardiac cycles for patients having

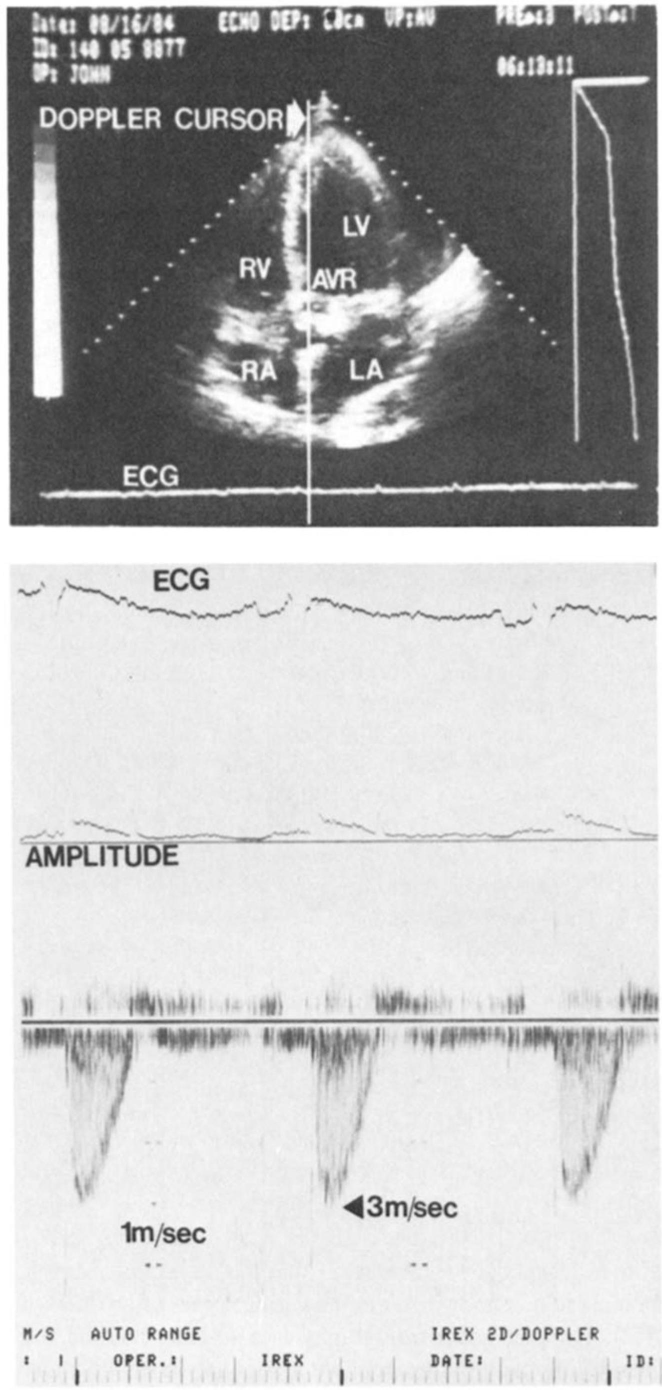

Figure 1. Two-dimensional echocardiographic apical four chamber view (**top**) and continuous mode Doppler study (**bottom**) from a patient with a normal tissue Carpentier-Edwards 25 mm valve in the aortic position. The peak flow velocity measures 3 m/s with a calculated peak pressure gradient of 36 mm Hg and a mean gradient of 19 mm Hg. AVR = aortic valve replacement; ECG = electrocardiogram; LA = left atrium; LV = left ventricle; RA = right atrium; RV = right ventricle.

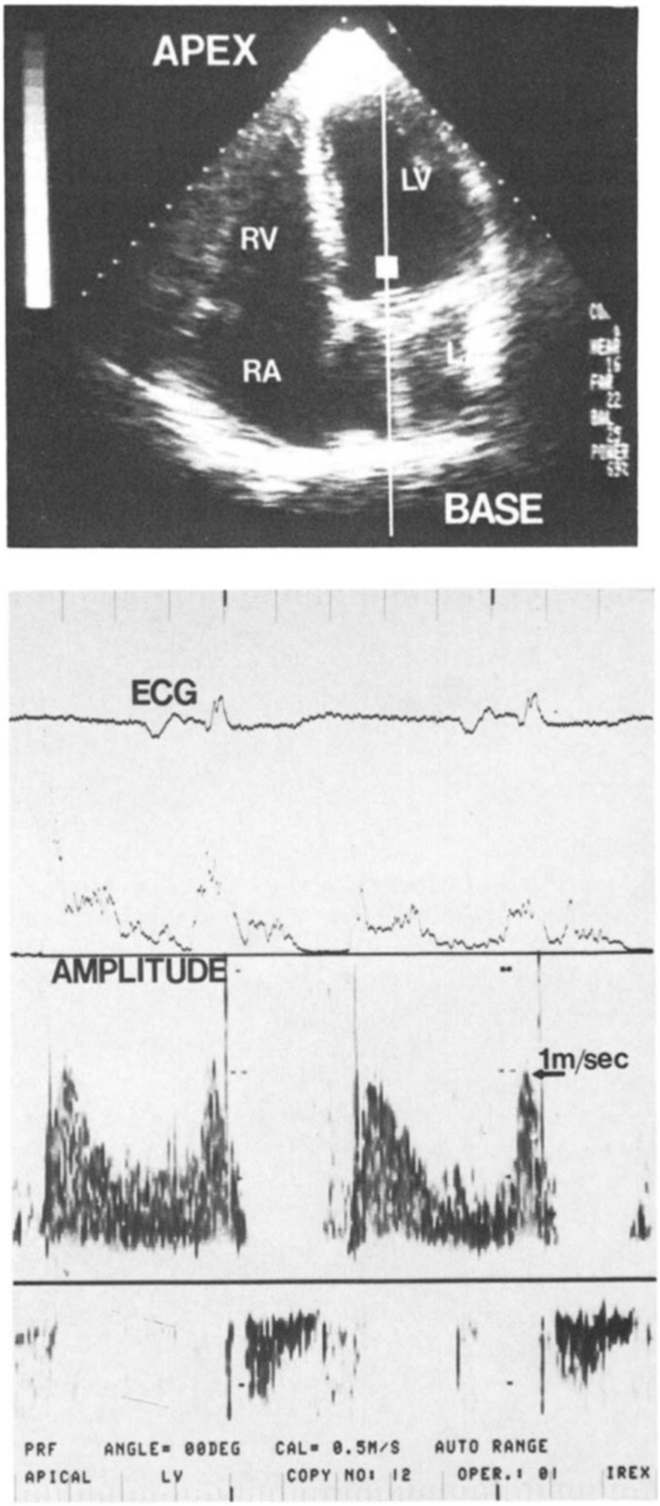

Figure 2. Two-dimensional echocardiographic apical four chamber view (**top**) and pulsed mode Doppler study (**bottom**) in a patient with a normal 31 mm St. Jude valve in the mitral position. The flow pattern resembles that of a normal native mitral valve. The peak velocity is only 1 m/s and the peak gradient is 4 mm Hg. MVR = mitral valve replacement; other abbreviations as in Figure 1.

normal sinus rhythm and five cardiac cycles for patients having atrial fibrillation.

Measurement of valvular regurgitation. The presence of mitral regurgitation was suggested by the detection of a holosystolic regurgitant jet below the prosthetic valve inside the left atrium. Care was taken to examine the area of the left atrium behind the prosthetic valve in detail to exclude the presence of an eccentric regurgitant jet. Using a mapping technique of the regurgitant jet into the left atrium (5), mitral regurgitation was considered minimal or mild when the regurgitant jet was detected immediately below the prosthetic valve and significant (moderate or severe) when the regurgitant jet was detected at least in the mid left atrium or beyond that into the distant left atrial cavity. The presence of aortic regurgitation was suggested by the detection of a diastolic regurgitant jet in the left ventricular outflow tract. With a similar mapping technique, aortic regurgitation was considered minimal or mild when the regurgitant jet was found immediately below the prosthetic aortic valve, and significant when it was recorded in both the apical and the left parasternal long-axis views and at least 2 cm inside the left ventricular outflow tract.

Statistical analysis. Statistical comparison of peak velocity, peak and mean gradient and prosthetic valve orifice (for the mitral position only) among the various types of prosthetic valves as well as among the different sizes of the St. Jude valve in the aortic or mitral position was performed using analysis of variance with Tukey's range test and Bonferroni t test correction for multiple t tests. All values are expressed as mean ± SD and range. A probability (p) value of 0.05 or less is considered statistically significant.

Results

Normally Functioning Prosthetic Valves

Peak velocity and gradient. The peak velocity (in meters per second), the peak and mean transvalvular gradients (in millimeters of mercury), the incidence of regurgitation of various prosthetic valves in the aortic or mitral position and the calculated prosthetic valve orifice in the mitral position are shown in Table 1. The peak velocity and the peak and mean gradients of the St. Jude valve in the aortic position were lower than in those of the Björk-Shiley, Starr-Edwards or tissue valve, but these differences reached statistical significance only when compared with the Starr-Edwards valve. In the mitral position, the peak velocity and peak and mean gradient of the St. Jude and Björk-Shiley valves were similar and somewhat lower than those of the Beall, Starr-Edwards or tissue valve. The St. Jude valve in the mitral position had the largest estimated valve orifice, whereas the Beall and tissue valve prostheses had the smallest.

When patients with a size 19, 21, 23 or 25 St. Jude valve in the aortic position were compared, peak velocity and

Table 1. Peak Velocity, Peak and Mean Gradient, Incidence of Regurgitation and Calculated Valve Area (in mitral position only) in 133 Patients With Various Types of Prosthetic Valves in the Aortic or Mitral Position

	St. Jude	Björk-Shiley	Beall	Starr-Edwards	Tissue
Aortic position (n = 59)					
Number of patients	38	8	—	4	9
Peak velocity (m/s)	2.3 ± 0.6*	2.6 ± 0.5	—	3.2 ± 0.2	2.6 ± 0.6
	(1.0 to 3.9)	(1.8 to 3.0)	—	(3.0 to 3.3)	(1.8 to 3.6)
Peak gradient (mm Hg)	22 ± 12*	27 ± 9	—	40 ± 3	30 ± 12
	(4 to 61)	(13 to 36)	—	(36 to 43)	(12 to 53)
Mean gradient (mm Hg)	12 ± 7*	14 ± 6	—	24 ± 4	17 ± 10
	(2 to 32)	(6 to 23)	—	(19 to 27)	(5 to 36)
Regurgitation	22 (58%)	5 (62%)	—	3	4 (44%)
Mitral position (n = 74)					
Number of patients	44	8	13	3	6
Peak velocity (m/s)	1.6 ± 0.3	1.6 ± 0.3	1.8 ± 0.2	1.8 ± 0.4	1.9 ± 0.3
	(1.0 to 2.5)	(1.0 to 2.0)	(1.5 to 2.3)	(1.5 to 2.3)	(1.6 to 2.3)
Peak gradient (mm Hg)	11 ± 4	10 ± 3	13 ± 4	13 ± 5	15 ± 5
	(4 to 24)	(5 to 16)	(9 to 21)	(19 to 23)	(10 to 23)
Mean gradient (mm Hg)	5 ± 2	5 ± 2	6 ± 2	5 ± 2	7 ± 1
	(1 to 14)	(2 to 7)	(4 to 10)	(3 to 8)	(5 to 8)
Orifice (cm²)	3.0 ± 0.6†	2.2 ± 0.4	1.7 ± 0.2	2.1 ± 0.5	2.2 ± 0.7
	(1.8 to 5.0)	(1.6 to 2.7)	(1.3 to 2.0)	(1.7 to 2.3)	(1.1 to 3.2)
Regurgitation	14 (32%)	3 (38%)	0	1	0

*$p < 0.05$ compared with Starr-Edwards; †$p < 0.0001$ compared with all other valves. Numbers in parentheses indicate range. n = number of patients.

peak and mean gradients tended to be higher in patients with a smaller valve size; these differences, however, did not reach statistical significance. There was also no significant difference in these measurements when patients with a size 27, 29 or 31 St. Jude valve in the mitral position were compared (Table 2).

Valve regurgitation. Insignificant (minimal or mild) aortic regurgitation was detected by Doppler technique in 58% of patients with a St. Jude valve, 62% of patients with a Björk-Shiley valve in the aortic position, 32% of patients with a St. Jude valve and 38% of patients with a Björk-Shiley valve in the mitral position. Insignificant regurgitation was also found in patients with a Starr-Edwards or tissue valve in the aortic position; mitral regurgitation was not detected in patients with a Beall or tissue valve in the mitral position.

Tricuspid prostheses. The two patients with a Björk-Shiley valve in the tricuspid position had, respectively, a peak velocity of 1.3 and 1.9 m/s, a peak gradient of 6 and 15 mm Hg and a mean gradient of 3 and 7 mm Hg. One patient with a Hancock prosthesis in the tricuspid position had a peak velocity of 1.9 m/s and a peak and mean gradient of 14 and 8 mm Hg, respectively. None of these three patients had tricuspid regurgitation by Doppler technique.

Malfunctioning Prosthetic Valves

The clinical, hemodynamic and Doppler echocardiographic findings in 17 patients with complications related to the prosthetic valves are shown in Table 3. Prosthetic valve malfunction was proven by cardiac catheterization or at surgery in 14 of the patients; 2 of these patients underwent surgery based on the Doppler findings without prior catheterization. Two patients died immediately after the Doppler study and before corrective surgery could be performed; the diagnosis was confirmed at autopsy in both. In one patient with a tissue valve and severe mitral regurgitation by Doppler echocardiography, catheterization and surgery were not performed because of the patient's poor general condition and the high surgical risk.

St. Jude valve. Four patients with a St. Jude valve (three in the aortic and one in the mitral position) had a paravalvular leak and presented with congestive heart failure 1 to 7 months after surgery. All four patients had evidence of significant regurgitation by Doppler study, and in two of them the forward velocity and gradient across the prosthetic St. Jude valve were significantly higher than the normal values of a similarly sized St. Jude valve in the same position (Table 2). After surgical repair of the leak, the forward peak velocity decreased and regurgitation was no longer present (Fig. 3).

Björk-Shiley valve. Two patients with a Björk-Shiley valve (one in the aortic and one in the mitral position) had a paravalvular leak and valve thrombosis, respectively. Doppler study did show significant aortic regurgitation in the first patient, but no forward flow across the mitral prosthesis or mitral regurgitation could be recorded in the patient with valve thrombosis. The latter patient was not taking warfarin and he died before surgery could be undertaken; a

Table 2. Peak Velocity and Peak and Mean Gradient in 73 Patients With a St. Jude Prosthesis

Size	No. of Patients	Peak Velocity (m/s)*	Gradient (mm Hg)* Peak	Mean
Aortic position				
19	4	3.0 ± 0.8 (2.1 to 3.9)	38 ± 20 (18 to 61)	22 ± 11 (10 to 32)
21	6	2.5 ± 0.4 (1.8 to 2.9)	26 ± 7 (13 to 34)	13 ± 5 (6 to 21)
23	14	2.2 ± 0.6 (1.0 to 3.3)	21 ± 12 (4 to 44)	10 ± 7 (2 to 29)
25	9	2.2 ± 0.5 (1.5 to 3.0)	20 ± 9 (8 to 36)	11 ± 6 (3 to 22)
Mitral position				
27	8	1.6 ± 0.3 (1.2 to 2.1)	11 ± 4 (6 to 17)	5 ± 2 (1 to 7)
29	17	1.6 ± 0.3 (1.1 to 2.2)	10 ± 3 (5 to 19)	4 ± 2 (2 to 8)
31	15	1.7 ± 0.4 (1.0 to 2.5)	12 ± 6 (4 to 24)	5 ± 3 (2 to 14)

*No statistically significant difference is found among the different sizes in aortic or mitral positions. Numbers in parentheses indicate range.

severely fibrotic and thrombosed Björk-Shiley prosthesis was found at autopsy.

Beall valve. Three patients with a Beall 104 mitral prosthesis had complications related to the disc (disc wear in two patients and disc dehiscence in one patient) 11 to 12 years after the valve insertion. In the patient with valve dehiscence, significant mitral regurgitation was detected by Doppler study (Fig. 4). In the other two patients, mitral regurgitation was not detected, although cardiac catheterization did reveal 1½+ and 3+ mitral regurgitation, respectively. In one of these patients, however, the disc cocking and the resulting mitral regurgitation were intermittent. In another patient with a Beall 106 prosthesis, significant mitral regurgitation probably due to a paravalvular leak was

Table 3. Clinical, Hemodynamic and Doppler Echocardiographic Findings in 17 Patients With a Malfunctioning Prosthetic Valve

Case	Age (yr) & Sex	Type of Valve	Position	Complication	Time From Insertion	Cath	Doppler Study: Gradient (mm Hg) Peak	Mean	Regurgitation	Outcome
1	76M	St. Jude 23	A	Paravalv leak	1 mo	2 to 3 + AR	55	37	Significant	Repair
2	73F	St. Jude 19	A	Paravalv leak	5 mo	3 + AR	44	18	Significant	Repair
3	55F	St. Jude 19	A	Paravalv leak	7 mo	3 + AR	45	18	Significant	Repair
4	57F	St. Jude 29	Mi	Paravalv leak	1 mo	Not done	31	8	Significant	Repair
5	62M	B-S 25	A	Paravalv leak	7 yr	2 + AR	26	14	Significant	Replacement
6	59F	B-S 27	Mi	Thrombosis*	18 mo	1 + MR	—	—	Not found	Death
7	60M	Beall 104	Mi	Dehiscence	11 yr	Not Done	16	9	Significant	Death
8	41M	Beall 104	Mi	Disc wear	11 yr	2 + MR	20	5	Not found	Replacement
9	63M	Beall 104	Mi	Disc cocking	12 yr	3 + MR	16	6	Not found	Replacement
10	43M	Beall 106	Mi	Paravalv leak	12 yr	1 to 2 + MR	17	7	Mild	Replacement
11	33M	Hancock 27	Mi, T	Endocarditis	7 yr	Not done	25	17	Significant	Death
12	68F	Hancock 27	Mi	Degeneration	7 yr	3 + MR	36	18	Minimal	Replacement
13	75F	C-E 31	Mi	Degeneration	6 yr	3 + MR	15	5	Significant	Replacement
14	72M	C-E 29	Mi	Degeneration	7 yr	3 + MR	11	4	Significant	Medical Rx
15	77M	C-E 31	Mi	Degeneration	6 yr	3 + MR	23	8	Significant	Medical Rx
16	72F	I-S 21	A	Paravalv leak	2 yr	4 + AR	39	20	Significant	Replacement
17	63F	I-S 29	Mi	Endocarditis	1 mo	Not Done	18	8	Significant	Replacement

*Patient discontinued warfarin. A = aortic; AR = aortic regurgitation; B-S = Björk-Shiley; Cath = cardiac catheterization; C-E = Carpentier-Edwards; F = female; I-S = Ionescu-Shiley; M = male; Mi = mitral; MR = mitral regurgitation; paravalv = paravalvular; Rx = treatment; T = tricuspid.

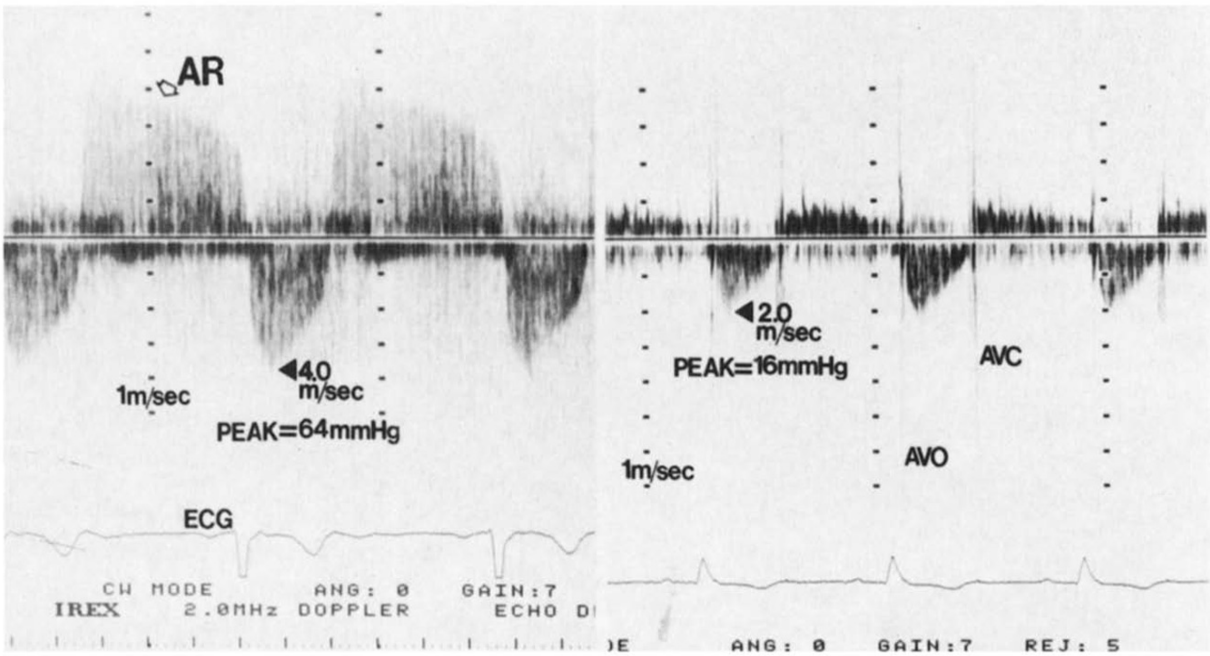

Figure 3. Continuous mode Doppler recordings in a patient with a size 23 St. Jude valve in the aortic position and a paravalvular leak. Aortic regurgitation (AR) is present (**left**) and the forward peak velocity across the prosthetic valve measures 4 m/s, corresponding to a peak gradient of 64 mm Hg that is related to the regurgitation. At surgery, the valve was not stenotic, and after repair of the paravalvular leak (**right**) the forward peak velocity decreased to 2 m/s (peak gradient 16 mm Hg) and aortic regurgitation was no longer detected. The spikes of aortic valve opening (AVO) and closure (AVC) are shown. ECG = electrocardiogram.

detected by Doppler echocardiography and was confirmed by cardiac catheterization.

Tissue valve. Seven patients had a malfunctioning tissue valve including two with a Hancock prosthesis, two with an Ionescu-Shiley valve and three with a Carpentier-Edwards valve. One patient with a Hancock prosthesis in the mitral and tricuspid positions was an intravenous drug abuser with repeated episodes of endocarditis after insertion of the valves and persistent heart failure. Doppler study revealed significant mitral and tricuspid regurgitation and an increased pressure gradient across both the mitral and tricuspid prostheses (Fig. 5). The second patient with a Hancock prosthesis in the mitral position had valve degeneration and heart failure 7 years after the valve insertion. Doppler study showed minimal mitral regurgitation but values for peak and mean gradient across the prosthetic valve were higher than the normal range of values for tissue valves (Fig. 6) (Table 1). Two patients with an Ionescu-Shiley valve (one in the mitral and one in the aortic position) had a paravalvular leak and significant regurgitation detected by Doppler echocardiography. Finally, three patients with a Carpentier-Edwards prosthesis in the mitral position had valve degeneration 6 to 7 years after valve insertion. All three patients had significant mitral regurgitation detected by Doppler study and, in one of them, the forward velocity and gradient across the prosthesis were significantly increased. Overall, Doppler echocardiography correctly identified the presence of regurgitation in all seven patients with tissue valve prostheses and showed higher than normal values for forward velocity and peak and mean gradients across the prosthetic valve in three patients.

Echocardiography. Two-dimensional echocardiography was abnormal in only 3 (all with a tissue valve) of the 17 patients; vegetations were seen in 2 patients with endocarditis (Fig. 5), and significant thickening and restriction of leaflets was evident in one patient with degeneration of the Hancock prosthesis (Fig. 6).

Discussion

Pressure gradients in normal prosthetic valves. The pressure gradient across a valvular obstruction can be calculated by Doppler echocardiography using the simplified Bernoulli equation: pressure gradient = 4 × (maximal velocity)^2. The reliability of Doppler measurements of the pressure gradient across native and prosthetic valves has been validated by angiographic methods (3,12). In this study, we report the peak velocity, the peak and mean gradients and the valve orifice (in the mitral position only) of 136 consecutive patients with a normally functioning metallic or tissue prosthetic valve (Table 1). The majority of our patients had a St. Jude bileaflet mechanical prosthesis. In the aortic position, the St. Jude valve had the lowest values for peak velocity and peak and mean gradients. In the mitral position, all valves had similar peak velocities and pressure gradients, but the St. Jude valve had a significantly larger

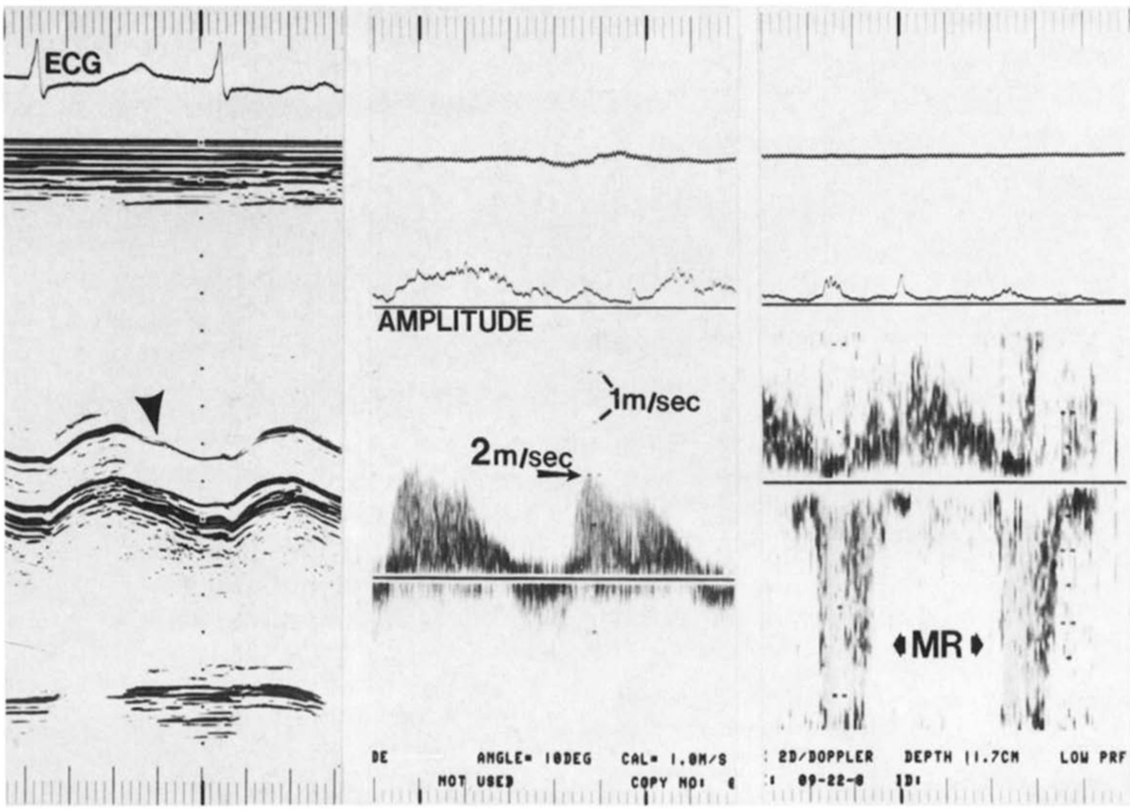

Figure 4. M-mode echocardiogram (**left**) and pulsed mode Doppler study with sampling in the left ventricle (**middle**) and left atrium (**right**) in a patient with a Beall valve in the mitral position and disc dehiscence. Only the valve stents are visualized on the M-mode recording (**arrowhead**); the disc is absent. Forward velocity across the prosthetic valve is 2 m/s (**middle**); mitral regurgitation (MR) is evident (**small arrowheads** in **right panel**). ECG = electrocardiogram.

calculated orifice. The hemodynamic advantages of the St. Jude valve, which include a lower transvalvular gradient and a larger effective valve area, especially in smaller anular sizes, have also been demonstrated by angiographic studies (13). Patients with a St. Jude valve and a smaller valve size (19 mm) in the aortic position tended to have a higher peak velocity and mean and peak pressure gradients (Table 2).

The status of cardiac output and the positioning of the Doppler beam as parallel as possible to the flow through the prosthesis may affect the recording of the maximal velocity and the calculation of pressure gradients. Doppler echocardiographic evaluation of flow characteristics of central flow valves like the tissue and St. Jude valves or semicentral flow valves like the Björk-Shiley in our study was easier than the Doppler assessment of peripheral flow valves like the Starr-Edwards and Beall valves, especially in the mitral position (14). Multiple views and transducer orientation were necessary to obtain optimal velocity profiles and peak velocity signals in the latter valves. The sample volume of the pulsed Doppler or continuous wave beam often had to be placed alongside the ball or disc at the sewing ring to obtain adequate tracings.

The pressure gradients estimated by Doppler echocardiography in our study for the Björk-Shiley, Starr-Edwards and tissue valves are similar to those reported in cardiac catheterization (15) and prior Doppler studies (7,14). The peak velocities found in our patients with a St. Jude valve were also similar to, although slightly higher than, those reported by Weinstein et al. (6) in 20 patients with a normally functioning St. Jude valve (2.3 ± 0.6 versus 2.0 ± 0.5 m/s for the aortic position and 1.6 ± 0.3 versus 1.4 ± 0.3 m/s for the mitral position).

Regurgitation in normal prosthetic valves. Minimal or mild degrees of aortic or mitral regurgitation have been found by angiography in patients with a normally functioning St. Jude (16,17) or Björk-Shiley valve (18). This "physiologic regurgitation" is negligible from a hemodynamic point of view and appears on the aortogram or left ventriculogram as a slight subvalvular reflux of contrast medium. The regurgitation in the disc valves is probably transvalvular and tends to be more pronounced in patients with a larger valve. We have found evidence of aortic regurgitation by phonocardiography in 15% of patients and by M-mode echocardiography in 22% of patients with a normally functioning St. Jude valve in the aortic position (19). In the present

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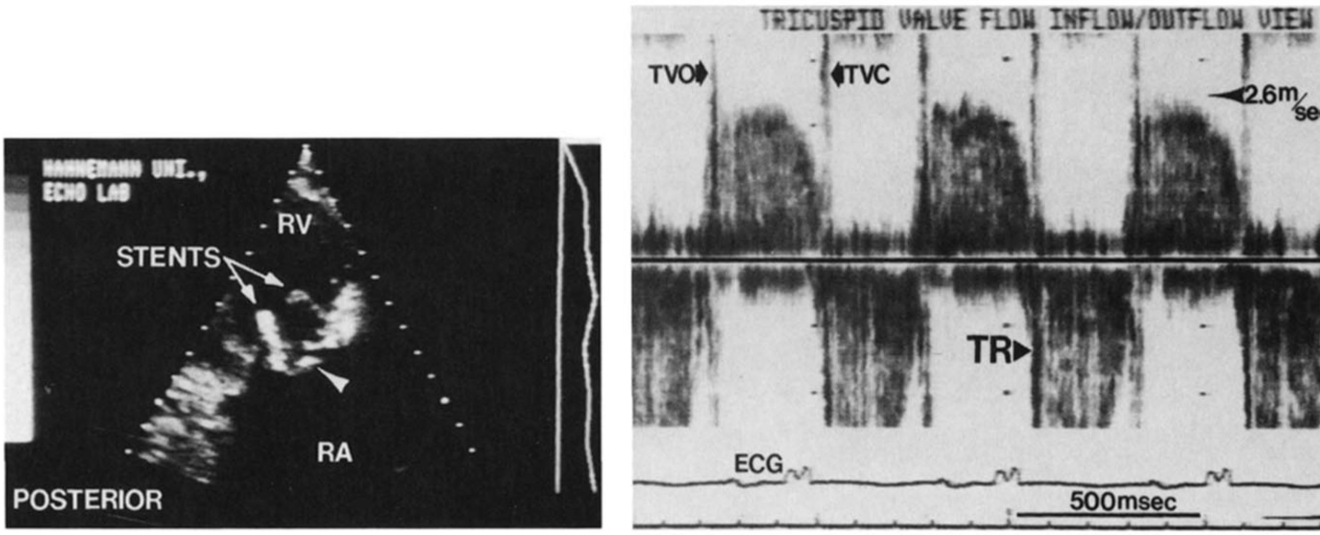

Figure 5. Two-dimensional echocardiographic right ventricular (RV) inflow-outflow view (**left**) and continuous mode Doppler study (**right**) in a drug addict with a Hancock tissue valve in the tricuspid position and repeated episodes of endocarditis. Focal thickening of the cusps in the echocardiogram suggests vegetations (**arrowhead**). The peak velocity across the bioprosthesis measures 2.6 m/s with a calculated peak gradient of 27 mm Hg and a mean gradient of 20 mm Hg. Tricuspid regurgitation (TR) is also present. The spikes of the prosthetic tricuspid valve opening (TVO) and closure (TVC) are shown. Other abbreviations as in Figure 1.

study, minimal or mild aortic regurgitation was detected by Doppler echocardiography in 58% of patients with a St. Jude valve and in 62% of patients with a Björk-Shiley valve. Regurgitation in the mitral position was less common (32% in the St. Jude and 38% in the Björk-Shiley valve). Mild aortic regurgitation by Doppler echocardiography was recently reported (14) in 42% of Björk-Shiley valves, 26% of porcine valves and 33% of Starr-Edwards valves. A diastolic murmur is usually not audible in these patients; its definite presence should indicate closer follow-up of the patient for the possibility of a paravalvular leak (1).

Because it may be difficult to distinguish paravalvular from transvalvular leaks, and "physiologic" from pathologic regurgitation by pulsed mode Doppler studies, using a mapping technique of the regurgitant jet may be helpful. Detection of the regurgitant jet more than 2 cm into the left ventricular cavity or the left atrium is often suggestive of significant aortic or mitral regurgitation (14). Another useful sign suggesting the presence of significant regurgitation is the recording of a high forward peak velocity across the prosthesis, provided that the patient has preserved cardiac output (Fig. 3). "Physiologic" regurgitation is less common in Starr-Edwards and tissue prosthetic valves (14,20,21), whereas mitral regurgitation is an abnormal finding in patients with a Beall valve.

Value of Doppler echocardiography in assessing prosthetic valve malfunction. In our study, Doppler echocardiography correctly identified the complication in 15 (88%) of 17 patients with a malfunctioning prosthetic valve (10 metallic and 7 tissue valves) (Table 3). Significant regurgitation due to a paravalvular leak or prosthetic valve endocarditis was detected by Doppler technique in nine patients and was confirmed by cardiac catheterization. In two patients with a Beall 104 prosthesis, mitral regurgitation could not be detected and in one patient with a Hancock prosthesis, the severity of mitral regurgitation was underestimated by Doppler study. The regurgitant jet across prosthetic valves can be eccentric and difficult to detect by pulsed mode Doppler technique; care should be taken to interrogate the area below the prosthetic valve in different views and directions. An increased forward peak velocity across the prosthetic valve compared with normal values was observed in patients with significant aortic or mitral regurgitation (Fig. 3) (10). Increased peak velocity can also result from obstruction of the prosthetic valve due to thrombosis or tissue valve degeneration (11) (Fig. 6). In one patient with a thrombosed Björk-Shiley valve, no flow could be detected by Doppler study because of complete obstruction of the valve by the thrombus; this patient died before corrective surgery could be undertaken. In two patients, the Doppler findings were sufficiently diagnostic so that corrective surgery was performed without preoperative cardiac catheterization.

Reproducibility and accuracy. Doppler measurements of flow velocity across normally functioning prosthetic valves are influenced by the valve size and left ventricular function, but they usually remain constant and have a good reproducibility in the same patient (14,22). Although baseline postoperative Doppler echocardiographic recordings were not available in our study, it is important to obtain such studies in patients with prosthetic valves so that longitudinal comparisons can be made with each patient serving as his

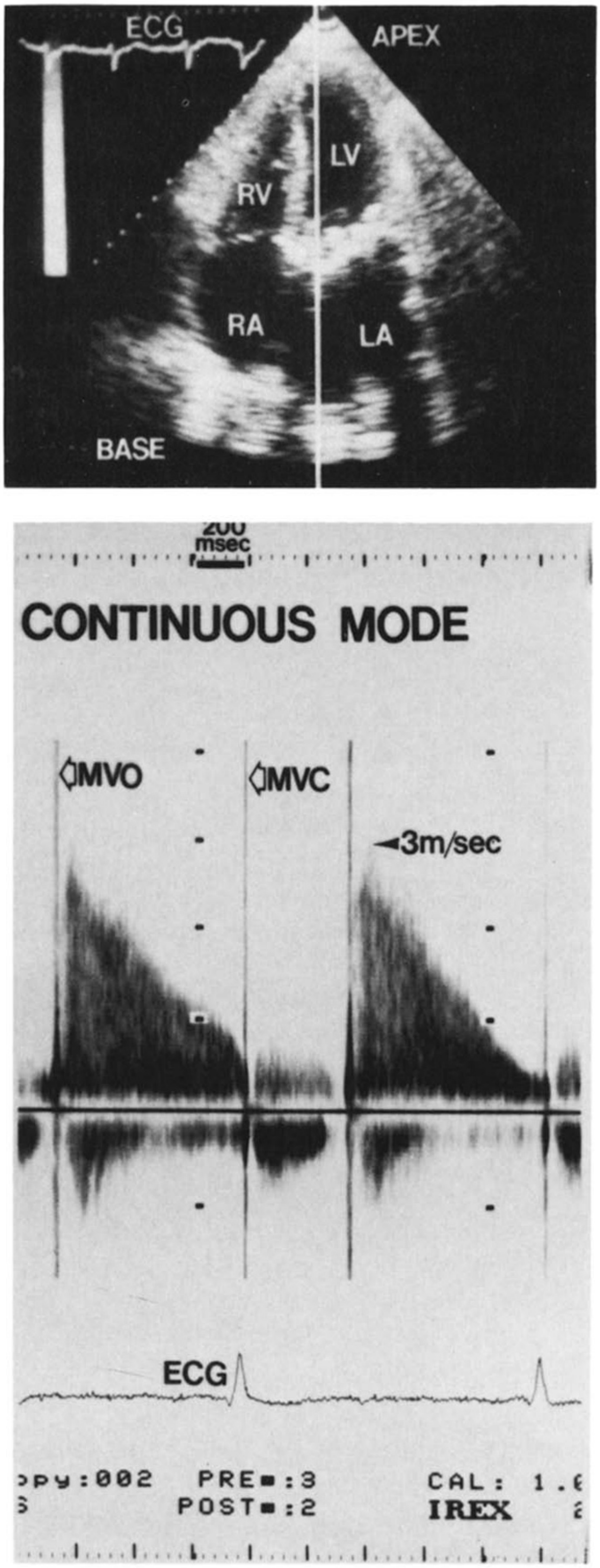

Figure 6. Two-dimensional echocardiographic apical four chamber view (**top**) and continuous mode Doppler study (**bottom**) in a patient with a Hancock 27 mm prosthesis in the mitral position and valve degeneration. The leaflets appear thickened. The peak velocity across the prosthetic valve is increased to 3 m/s, corresponding to a peak pressure gradient of 36 mm Hg (mean 18); the calculated prosthetic mitral valve orifice is 1.1 cm^2. The spikes of the prosthetic mitral valve opening (MVO) and closure (MVC) are also shown. Other abbreviations as in Figure 1.

or her own control when malfunction is suspected. The normal values for peak velocity and pressure gradients of various prosthetic valves reported in this study can serve only as a relative reference for comparison when malfunction is suspected and a baseline study is not available.

Doppler echocardiography may be superior to M-mode and two-dimensional echocardiography for assessing normal and abnormal prosthetic valve function. Weinstein et al. (6) described four patients with a St. Jude valve and paravalvular leak detected by Doppler ultrasound whose M-mode and two-dimensional studies did not demonstrate any abnormalities. Two-dimensional echocardiographic findings were abnormal in 3 of the 17 patients with a malfunctioning prosthetic valve in our study, and all 3 patients had a tissue valve in the mitral position (2 patients had vegetations and 1 had severe thickening and restriction of the leaflets).

Limitations of the study. The number of patients with different prosthetic valves (especially with Starr-Edwards and tissue valves) is relatively small in our study and therefore, no comparison among the various types of prostheses for the same valve size could be made. Although none of the 136 study patients who were assumed to have a normally functioning prosthetic valve had any clinical or echocardiographic evidence of malfunction, catheterization was not routinely performed, and because many of these patients were studied months or years after prosthetic valve insertion, subclinical or hemodynamically insignificant complications related to the prosthetic valve could not be entirely excluded. The true value of the Doppler technique in detecting prosthetic valve malfunction cannot be assessed from the results of our study alone. Most of our 17 patients with a malfunctioning prosthetic valve had been suspected clinically of having valve malfunction which was confirmed by Doppler studies; thus, they represent a highly selective population. For the same reason, the true incidence of malfunction of various prosthetic valves cannot be derived from the findings of our study.

Conclusions. Doppler echocardiography provides important quantitative information regarding the flow characteristics, pressure gradients and effective valve area (in the mitral position only) of various types of prosthetic valves. The St. Jude valve appears to have the most optimal hemodynamic properties compared with other metallic and tissue valves. Minimal or mild regurgitation is not uncommon in patients with a normally functioning St. Jude or Björk-

Shiley valve in the aortic or mitral position, and in patients with a Starr-Edwards or tissue valve in the aortic position. A baseline postoperative Doppler study would be useful for future comparisons when prosthetic valve malfunction is suspected. Doppler echocardiography can be a valuable adjunct to other noninvasive techniques in detecting malfunction of prosthetic valves, especially when St. Jude, Björk-Shiley and tissue valves are assessed.

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